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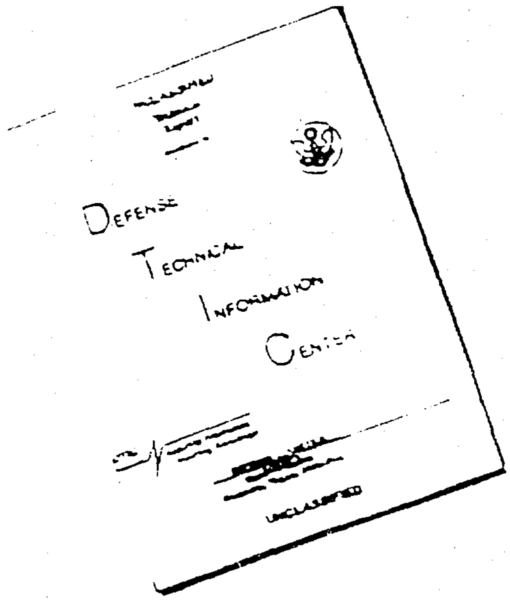

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This report summarizes the work under Contract F44620-73-C-0058 between Life Sciences, Inc. and the Air Force Office of Scientific Research. The work was concerned with studies of motion and visual interaction in simulator design and application. The specific objectives of the work were: (1) describe the characteristics of simulator motion and visual display in quantitative terms as experimental variables; (2) delineate measures of the dependent variables in terms of system output and pilot input measures, (3)

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identify and assign priorities to the experimental questions and formulate an overall plan for their investigation; (4) determine the capability and availability of the research equipment available for carrying out the experimental investigations; and (5) make recommendations for carrying out experiments based upon considerations of priority and research equipment capability and availability.

Due to the large number of experiments indicated, effort was concentrated on the development and test the performance equivalence method for determining training simulator characteristics which would be more economical of time and effort. This method proposes the comparison of the simulator and aircraft based upon the measured performance of the pilot in terms of control inputs to the two systems being compared. Data were collected in an instrumented T-37 training aircraft as the first step in carrying pilot performance to that in the ASUPT simulation system at Human Resources Laboratory Flying Training Division, Williams AFB. Due to administrative and scheduling constraints in collecting the aircraft data left time in the contract for only a preliminary analysis of these data. Equipment and scheduling constraints allowed for collection of data in ASUPT on only one pilot for one flight.

Preliminary analysis of the aircraft data indicate that these data can be used profitably in the derivation of measures of pilot performance for test of the performance equivalence concept. Since no time remained in the contract to carry out preliminary analysis of the ASUPT data no projections can be made as to the adequacy of these data.

An overall program of research on the motion-vision and their interaction problem was outlined based upon use of the T-37 aircraft data as a point of departure in configuring ASUPT as a criterion device. The carrying out of the plan if successful would provide quicker and more economical answers to both simulator characteristics and training methodology questions provided the necessary funds and personnel support could be brought to bear on the problem. It is recommended that the program be pursued.

ACKNOWLEDGEMENT

The work reported here has been made possible through the guidance and support of Drs. Charles Hutchinson, Glenn Finch and Ralph Canter of the Air Force Office of Scientific Research. Dr. W. V. Hagin and the technical staff of the Air Force Human Resources Laboratory, Flying Training Division have labored to keep the work relevant and practical. All of these efforts are truly appreciated.

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1.0 INTRODUCTION

Those concerned with the training of aircraft pilots have been working for a long while toward developing efficient and effective training methods. Their work has been directed toward methods which would reduce training cost and time and to increase its' quality and safety. Recent advances in the technology for producing complex training devices coupled with a greater need to conserve energy resources have resulted in increased interest in obtaining hard data for answering the questions about cost effective simulator design.

The investigations reported here were aimed at providing answers to a portion of these questions. Specifically, they were designed to obtain information for guidance in configuring the motion and external visual characteristics of training simulators to be used within the several levels of pilot training of the United States Air Force. It was expected that the findings would be generalizable to training in other tasks which require both motor skills and cognitive information processing. While the specific characteristics of training simulators to be investigated were the external visual display, simulator motion and their interaction, it was recognized that they could not be considered in isolation from other important variables acting in the training situation. Other characteristics of the simulator itself are important and interact with motion and vision. A second set of variables important to the effectiveness of the simulator are those subsumed under the rubric of training methodology. This latter category is concerned with such items as specificity of training objectives, sequencing of training objectives and tasks, methods of feed-back, cognitive integration and a host of other variables. It goes

without saying that these variables interact in the training situation and that the design of experiments aimed at specifying the degree or level of any one for effective training must consider the many levels of its interaction with the other variables. Determining all of the effects and combinations of effects would be a long and tedious process. The enormity of the number of experiments needed to provide answers to questions raised by these interactions using traditional experimental designs and methods caused the present study to become very much oriented toward the development of more efficient experimental and evaluative techniques. These techniques are discussed in detail in later sections.

The objective of obtaining specific data for recommendations and guidance required stating specific questions and defining certain procedures. These are stated and described in the paragraphs to follow.

1.1. DESCRIPTION OF INDEPENDENT VARIABLES

A first task was to describe and quantify the independent research variables within the areas of simulator motion and visual display. Although, to the experienced research worker this point would seem unnecessary of being made explicit, by far the greater proportion of research on these variables, particularly that of simulator motion, has been and is being carried out without explicit definition of the variable. It was felt to be an important premise that the research variables be defined in a manner independent from the present state-of-the-art for implementing them in simulators and along a dimension universally meaningful to the simulator design engineer. He could then implement the findings in the most efficient way that he could devise based upon the state of the engineering art at the time.

1.2 SCALING OF VARIABLES

A second and corollary task to be addressed in dealing with the research variables was the means for establishing the perceptual range and the scaling interval of the variables. The answer to this question bears directly upon how the variables might be used in other experimental paradigms. More importantly, it provides direct information to those concerned with designing and procuring simulators as to the degree to which variables ordinarily expressed in physical "hardware terms" are perceived and acted upon by the operator of the system.

1.3 DEPENDENT VARIABLE MEASUREMENT

The third major area of concern was with the measures and methods by which the resultant or dependent effects of varying the experimental variables was to be assessed. Corollary to the specification of the measurement and scaling of the independent variable is the effect variations has upon the outcome of interest. Traditional methods of looking at the output of the total system, while appropriate when the total system output is the only interest, can be misleading when the experimental question is concerned with the effect variation in the system has upon the control behavior of the operator. Particular emphasis is placed upon this point in this study because of its importance to training in the aircraft control task in simulators and because of the resistance with which the concept has been met within the research community. Emphasis in this report has been placed upon the extreme importance of looking at the operator's output behavior when evaluating or comparing systems in which the operator is being trained as a closed loop compensatory controller. Ignoring measurement of the controller's output is to be ignorant

of the behavior being shaped by the training device.

1.4 IDENTIFYING EXPERIMENTAL QUESTIONS

The fourth area of concern in the present study was that of bringing together and assimilating what is known about the effects of motion, vision and their interaction in the simulator situation; making explicit certain experimental questions to be answered; and assigning priorities to those questions. The criteria for priorities can change as conditions and requirements within the Air Force and its working environment change. For example, the necessity for making decisions about simulators for specific systems under development and procurement may bring added pressure for data upon which to base decisions specific to those systems. At the same time such particular and specific questions must be weighed against the necessity for defining basic questions and obtaining data generalizable across many systems. Often this latter research is put aside in favor of answering a specific question at a given time or utilizing a specific piece of experimental apparatus.

1.5 RESEARCH EQUIPMENT, CAPABILITY AND AVAILABILITY

A further important factor in setting priorities and obtaining answers is the availability and capability of research equipment and resources for obtaining empirical data. It should be axiomatic in experimental research that the experimental question should be stated specifically; experimental variables defined explicitly; the measurement techniques delineated; and finally, the experimental apparatus designed and procured for investigation of the stated questions. This utopia is rarely obtainable even for rather simple questions dealt with in a laboratory situation. It is certainly less likely to be realized in

working with the complex problems being dealt with in pilot training with its requirement for complex advanced state-of-the-art and expensive research equipment. The equipment designed to be the most complete for studying the questions addressed in this study was felt to be the ASUPT simulator located at the Air Force Human Resources Laboratory, Flying Training Division, AFSC, Williams Air Force Base. It was, therefore, a part of intent of this project to determine the capabilities of this research equipment and to use this capability as one of the factors in determining research priorities.

I. RECOMMENDED RESEARCH

Based upon the considerations and findings in the above five paragraphs it was the purpose of this study to combine this information with that of a parallel study of training research priorities based upon the concensus of experts in the field and to evolve a short and long term research program specific to obtaining answers to the questions of vision and motion simulation in pilot training simulators. It was also to be the responsibility of personnel involved in this project to assist in the conduct of critical experiments in the high priorty areas, analysis of the data and interpretation and application of the results.

It is the purpose of this report to summarize the progress and the problems in attempting to carry out the activities listed in the above paragraphs, as guidance both for the design of simulators and for future research.

2.0 DESCRIPTION OF EXPERIMENTAL VARIABLES

2.1 MOTION VARIABLES

It was indicated in the earlier section that one of the important items to be accomplished in the project was the definition of the independent experimental variables. It was also indicated that specific definition of the motion variable is required in order to manipulate it as an independent variable. Just as importantly, it should be defined such that it is meaningful and useful to the simulator design engineer.

Motion, as it may be sensed by the operator and influence his control behavior, has been considered in this study as being of two major types. These are (1) external forcing functions of which there are two sub-categories, and (2) movement as a result of control movement.

2.1.1 External Forcing Functions

The external forcing function to which the system (aircraft) reacts and to which the operator in turn responds may be imparted to the system through changes in air density or movement (turbulence), or they may be inputs to the system, either external or internal, which may be termed abnormal or catastrophic inputs. Each of these two types is elaborated in the paragraphs below.

The most important type of aircraft motion which must be identified and described is that of the response of the aircraft to the normal and continuously acting inputs to it from the turbulence to which it is subjected. In examining this source of motion, interest is upon its effect upon pilot's ability to carry out the compensatory control activities required to direct his aircraft through three-dimensional space.

in order to direct his aircraft through this space he must exert direct control over the pitch, roll, and yaw axes of his aircraft. External forces which tend to force his aircraft from the attitude which he is attempting to maintain must be sensed by him and corrections made.

The major disturbances to his aircraft from these external forcing functions act to disturb the system in pitch, roll and along the z or heave axis. The operator's sensing of these disturbances can serve as cues to him in exercising control over the pitch, roll and the yaw axes and thus null the error. It is, therefore, important that the response characteristics of the system being controlled, as it is disturbed in its operating environment, be identified and described in a quantitative fashion so that its importance to operator control may be determined.

The second type of forcing function is similar in its effect to a turbulence input but can be differentiated in that it is ordinarily not continuous and may require a very rapid but rarely occuring response on the part of the controller. An often cited example of this is the sudden loss of power in an outboard engine on a transport type aircraft. In such a situation the sensed motion may provide the operator with the information necessary for him to make corrective inputs into the system.

2.1.2 Control Input Motion

The second major type of motion is that which the system makes in response to inputs into the controls. The immediate feedback to the operator after making a control input is the motion of the system about the pitch, roll and yaw axes and in response to changes in power or thrust. An important source of movement in some systems is its response to the release of stores of various kinds. This response can be

considered an external forcing function leading to a disturbance in the system to be sensed and controlled by the operator.

It was pointed out in Section I that a highly complex interaction of variables must be considered in studying the characteristics of simulators of aircraft. With respect to control movement motion it is believed necessary to point out at this time the importance of the kinesthetic feedback from the controls and its relationship to motion and visual feedback in trainers and simulators of aircraft. In such systems when the operator is attempting to perform a compensatory tracking task and to null errors as they occur, a deviation from the standard may come about as a function of either a control input or as a result of an externally applied forcing function. It is important to the operator in his performance of precise control that he be able to separate those deviations occurring from external forcing functions and those occurring as a result of control movement and that he be able to do this on a proportional basis. That is to say that it is necessary for him to learn, based upon kinesthetic feedback from his control, what deviation to expect for a given amount of control input so that if simultaneous to his control input an external forcing function acts either to amplify or attentuate the deviation he can identify it and adapt his control accordingly.

2.1.3 Motion as an Experimental Variable in the Simulator

One of the major deterents to obtaining objective and generalizable data with respect to the relationship between motion and performance has been the lack of specificity in the definition of motion as an experi-

mental variable. Often no hint of the characteristics of the motion platform under investigation is given. Unless simulator platform motion is defined in terms and with a metric which allows its precise implementation as an experimental variable or as a design parameter the question of the effect of motion will remain in limbo.

The basic problem in defining simulator motion is to establish a means of measuring the physical fact of the motion of a platform so that the amount of motion can be varied in precise measurable ways and to do this in a way in which is meaningful and useful to the simulator design engineer.

The physical reality of the change in position of a mass such as a simulator motion platform may be modeled and described mathematically through description of that change in position and the derivatives of that change. The fidelity problem in simulation is one, first of all, of determining whether the changes of position of the platform and the derivatives of those changes are like those exhibited by the vehicle being simulated, i.e., the aircraft. Obviously the simulator does not duplicate the aircraft with respect to the magnitude of the changes in position. It may be made to duplicate the aircraft with respect to certain of derivatives provided that the results of the integration of these derivatives does not exceed some final value. We can do this by setting into motion a counter force or motion in the opposite direction come to be termed "washout".

The capability of a simulator motion platform for transmitting movement to the cockpit and to the pilot may be described quantitatively in terms of its ability to reproduce certain rates, accelerations, and

rates of onset of acceleration exhibited by the aircraft and perceived by the pilot as information pertinent to his control of the system. Due to the limited positional change capability of the simulator, however, the washback feature must be incorporated during which the same physical aspects of motion, i.e., rates, accelerations and rates of onset of accelerations are involved. In this case their magnitudes must be kept below the perceptable limits of the pilot.

The response of the simulator platform may be described as its ability to respond to a given input or impulse to the platform and this response could be described in terms of the way it moves over time. Thus, if the platform were driven by a sinusoidal input with varying frequency, the output or the way in which the platform followed this input could be plotted as a function of time, i.e., it could be described in the time domain. This method of looking at the response of the platform perhaps makes it more clearly understood how a platform, due to its particular characteristics, may not follow the input precisely. In part cular, as the input (the sinusoidal driving function) increases in frequency the platform may fall behind the input both in terms of the amplitude and the frequency of its response, i.e., it will begin to lag behind the input. These attributes of the response of the platform to a sinusoidal input may be described in terms of its frequency response and its phase lag, i.e., it may be described in the frequency domain.

An important consideration in the description of the response of the motion platform in the frequency domain is that of the driving or forcing function. A standard method for determining the frequency response of

the platform might be as indicated above, i.e., that of driving the platform with a given sinusoidal input and plotting its response. Thus, a motion platform could be configured to respond like the open-loop response of the aircraft with respect to rates of onset of accelerations, accelerations, rates and so forth. However, with the simulator platform an opposing movement must be initiated before impractical positional changes have taken place. Thus, if these opposing forces are initiated before large rates or positions have occurred the less complex the platform is likely to be. The question becomes one of whether or not the platform can be made to provide the pilot with useable motion cues to his control while it is limited to low positional and rate changes.

A note of caution must also be sounded with respect to the determination of the response frequency of the platform through use of an open-loop driving sinusoidal function. The open-loop test is a straight forward way of determining the transfer function of the device being examined, i.e., its ability to follow the input values and a description of how it follows. However, if the system is closed-loop system, i.e., an operator (pilot) is placed within the system, he senses the output and acts upon it in a particular way. We may find that he is adding something to his control which makes the system respond faster than it would appear to respond in solely open-loop fashion. That is to say, that the pilot may anticipate or act upon information received by him and make inputs into the system which provide lead or anticipatory information. The result would be to drive the system faster than it would appear to respond under the open-loop situation. Thus, the frequency response required in a

simulator platform might very well be higher than would appear to be necessary with an open-loop test comparison of the platform with the aircraft.

In any case, the frequency response method of examining the fidelity of motion characteristics of a simulator appears to be very feasible and one which is useful to the simulator design engineer. What is involved is the determination of the upper breakpoint frequency response of the simulator platform which determines how fast it will respond and the lower breakpoint frequency which determines in effect how fast it will washout or return. Past research would indicate that the upper breakpoint frequency of the platform should be, at least, 2.5 hz and the lower breakpoint frequency could be as high as .5 hz. However, these values are not well established and a useful research motion platform should be capable of responding up to approximately 3.5 hz at the upper breakpoint.

In summary, the description of the fidelity of simulation variable for any dimension of motion is recommended to be the frequency response of the platform to a standard driving input. The range of this frequency is recommended to be from 0 to 3.5 hz for a research simulator.

2.2 VISUAL DISPLAY VARIABLES

2.2.1 Visual System Designs

All visual simulation systems require that some method be devised to generate an image and some method also be devised to display that image. Taylor et al.[1] have listed four basic approaches to visual simulation, all of which are extant in one form or another in simulators in use today. These are (a) the model system approach, (b) the film projection system

approach, (c) a system involving transparency reconstruction, and (d) the electronic image generation system approach.

The model system involves the construction of a scale model of a scene to be simulated. A TV camera or other optical pickup device is usually placed on gimbals or servo mechanisms located over the model and the optical pick-up system then scans the model with the pilot operating the aircraft controls in the simulator according to the picture displayed.

Film projection systems provide two-dimensional representations of a three-dimensional scene via motion picture film or film strip.

In transparency reconstruction, according to Taylor et al., a constant high intensity beam of electrons is swept in time across the low persistence screen of a flying spot scanner in a specified raster pattern. The raster is focused on the transparency which modulates an intensity the light flux passing through it. This time varying flux is detected by light sensitive photo multipliers which in turn generate voltages proportional to the incident light flux.

Finally, these authors list electronic image generation. This involves the generation of a visual image by a digital computer system which has stored the data describing the visual environment in the computer memory and solves, in real-time, a mapping transformation function which defines the environment onto the display or image plane.

Two things are to be considered concerning the four general methods for generating visual displays. First, any attempt to specify and quantify independent variables for evaluation and/or generation of a visual simulation display should be independent of the technique which is called for in the development of the display. That is, specification

of the independent variables should not be contingent upon whether the images are developed from a model or from a transparency, etc. Second, the image, whether it is generated by any or all of these four listed above has certain characteristics which have been addressed by researchers in times past. It is to this second point that comments are now directed.

2.2.2 Visual Display Characteristics

Researchers have postulated several approaches to the evaluation of a visual display. In the evaluation of these displays there seems to be some consensus with respect to certain criteria which an image should attain in order to be acceptable. A convenient dichotomy has been proposed by Rougelot[2], who suggested that images should exhibit desired characteristics of quality and content. Qualitative characteristics he listed were brightness, resolution, color, focus, and contrast. He listed under the heading of content: wide field of view, realism (detail), unrestricted environment dynamics (e.g., controllable moving objects in the environment) and unrestricted environment coverage. Other researchers (e.g., Rosendahl[3], have indicated that all images should meet some criterion of resolution. He has suggested that in addition to resolution, sharpness of the optical image is important. He went further to suggest that acutance, which is the normalized mean square average of the slope of an edge trace, is a much better expression of image sharpness. Other researchers and/or documents (see for example the ATA Visual Simulation Sub-Committee recommendations for visual specifications for today's simulator[4]) also speak of such characteristics as brightness, resolution, contrast, distortion, perspective, etc.

The use of Rougelot's dichotomy is a convenient way to demonstrate that there are certain characteristics of a visual display which have to do with the quality of that display while there are certain other characteristics of this display which identify the image or display content. Further research into the background of this dichotomy (see for example Taylor et al.) indicates that image quality characteristics such as brightness, resolution, sharpness, contrast, distortion and perspective are reasonably well quantified and certain recommendations can be made to the engineer with respect to the amount of, say, distortion which should be permissible in a given visual display. It is the approach here that there are optimum qualitative characteristics of a visual display such that one would expect optimum perspective, little or no distortion, contrast within a specified range, a certain sharpness level on the part of the visual display and a display that meets some criterion for resolution and brightness. Therefore, the major emphasis in this report has been on those variables which could be subsumed under a heading of Image Content.

A second reason for pursuing variables under the heading of Image Content could be explained on the basis of the fact that these variables are not covered to any great extent in the literature. Thus, it is difficult to provide the design engineer with data in quantitative form which accurately and adequately defines the content which a visual image should possess for a given simulation requirement.

It is proposed that those variables to be considered initially under the heading Image Content are: detail, complexity (number of objects per unit area), realism, and texture.

2.2.3 Image Content Quantification

There are two approaches to the quantification of the variables listed under the heading Image Content. It is possible to specify a given content variable and propose the metric to be used to vary that variable along some continuum. It is also possible that one might experiment, as it were, with the variable in terms of qualitative differences in the variable to make some determination as to whether this variable merits further study. That is, some variables may be added, deleted, or changed as a function of the experimental conditions surrounding them. For that reason, some of the variables proposed have more precise definitions and a more precise metric than other variables and exploratory studies are needed before a final judgment is made to include or exclude these variables.

The conventional approach to the specification of these image content variables would dictate that one need merely count the number of objects within a given visual scene in order to describe the content of that image. However, this particular approach is lacking in that it is difficult to establish a rule or model on which to base the number of given objects one might include in a given scene. That is to say, one needs a rule for inclusion or exclusion of a given object or type of object within the scene. In addition, detail and image content are confounded in that one might establish the relative degree of image content on some scale from high to low and on the basis of the amount of detail judged to be present in a visual scene. Thus, a scene rated as having a high amount of detail would be judged as possessing a high level of image content. On the other hand, a scene with very little detail would be judged to be very low in image content. This may be one case of a more general condition but it

does not lend itself to quantification or description as an independent variable due to the fact that one has no convenient metric for the inclusion or exclusion of a given object or number of objects in the scene. It is also the case that a scene with very low detail could be judged as possessing a high level of content. That is to say, one might see a greater number of objects in a given field with a low level of detail per object. Because of this a paradigm is developed in the following discussion that dispenses with the notion of image content in the sense of the number of objects required in a given scene and approaches the category of image content on the basis of the cues required for the pilot to accomplish one of the several categories of maneuvers required of him. Figure 2.1 is a block diagram of the paradigm which shows two stages based on the type of information required to accomplish a particular task. These stages are predicated on the notion that the pilot requires two kinds of visual information in order to accomplish his task; position information and rate information. The paradigm itself was developed out of a model for visual discrimination (Thielges & Matheny[5]) which analyzes the visual scene external to the aircraft in terms of perspective geometry. That is, a picture plane is chosen to lie coincident with the aircraft windscreen and perpendicular to the eye line of regard so that an external referent is projected on this plane. Simultaneously an internal referent exists on the plane. Thus, the external and internal referents lie in juxtaposition one to the other and the essential task of the pilot is to detect perturbations of the vehicle on the basis of the relationship or change in the relationship of the internal and external referents on this picture plane.

Stage	Required In Image	Task Used For	Information Obtained
1.	System of Internal & External Referents	Detection & Identification of External Referent	Position
2.	Surface & Sky Texture	Identification & Tracking	Position & Rate Info.

Figure 2.1 Proposed Two-Stage Visual Cue Paradigm.

Referring to Figure 2.1, the first stage indicates that if one is given a system of referents (in this case the internal and external referents alluded to above) one may obtain position information from the juxtaposition of these referents and this juxtaposition will serve then for the detection and identification of an external referent. Alternately, the first stage considers the task of the pilot to be detection and identification of some external referent which is usually in the form of objects or scenes or targets within the field of view. This paradigm is independent of the maneuver required of the operator, i.e., whether it is to be take-off and landing, formation flight, etc. A given task might be to identify an external object which would be designated the external referent (ER) and which the pilot must identify and act upon. Identification of the external referent requires position information with respect to that external referent. For example, if the pilot were required to join up with another aircraft for formation flight the ER in the given field would be the aircraft with which the pilot must join. Thus, a system of external

referents is required in order to provide position information to accomplish the tasks of detection and identification of an external referent to which at some later time some meaning will be attached.

The second stage discusses an additional task in addition to identification; namely, tracking. In order to track a referent external to an aircraft the pilot is required to have some type of rate data to give him lead or predictive information. In this case rate data could be provided by surface or sky texture. These textures can be identified or defined as the textures of either the ground surface or, in the case of joining up with an additional aircraft in formation flight, the aircraft itself or other objects in the immediate vicinity of the pilot.

To recapitulate, the paradigm of image content for a given visual display has two parts which are divided on the basis of whether the individual must identify or whether he must track a given object within the scene. If detection and identification is the task then the subject needs positioning information which is provided by objects in the field. If the individual must then track these objects it is necessary to have rate information which can be provided by surface or sky texture. It should be noted at this point that for an individual to accomplish a given visual task he will be both identifying and tracking an external referent. Therefore, his task is actually one of time sharing between identification and tracking in a given maneuver and this maneuver dictates whether he is to spend most of his time identifying or most of his time tracking.

Finally, in its simplest form the model states that the two stages provide information for detection and identification through a system of

internal and external referents and provides for detection of rates through surface or sky texture. Although the model is incomplete it is convenient as a vehicle to test the first list of proposed variables, namely detail, complexity, realism and texture. Further, it is necessary to test these variables, in part because it is doubtful that one would find visual simulation systems acceptable which do not have a modicum of face validity. It is perhaps necessary that displays show or project images of what the pilot expects to see in the so-called real world situation, even if these add nothing of value to the training situation.

2.2.4 Image Content Variables

Complexity of content is operationally defined as the number of objects per unit area. Complexity, in the general sense, simply means how cluttered the image is. It is pertinent to our general model in that one can vary the level of complexity as defined above and thereby test certain tenents of the model with respect to embedding external referents in the image, placing the requirement on the pilot-observer to detect and identify the external referent and then act upon it. As such, complexity is one of those variables which was suggested earlier as one which should first take a categorical or qualitative form for further exploration. That is, one should not expect at the outset to be able to quantify the variable complexity without first investigating complexity on some molar level to make determinations as to what particular characteristics or parts of this variable complexity are amenable to quantification. Simply stated, a scene with a standard unit area which has relatively few objects discernible within that area would be considered a scene with a low level of complexity. In contrast a scene with a unit area which has a large

number of objects discernible within this area would be judged a scene a high level of complexity. For purposes of initial study, therefore, it is preferable to consider complexity in terms of categories of high and low levels (or simple vs. complex) with the relative numbers of objects within a given unit area operationally defining these categories. The outcome of experimentation with this variable is such that the variable would prove to be either a meaningless term or one which could be explored further with ultimate quantification of the objects in terms perhaps of optimum, minimum, and maximum requirements for the number of objects within a given unit area, not only on the basis of what is necessary and sufficient but what is judged to be acceptable to the observer.

Coincident with the construct complexity one needs also to consider the notion of realism. Realism, per se, of a given image is actually a meaningless term. In one sense it might be said that there is no such thing as a realistic scene. This is, at least, partly true from an objective point of view owing primarily to the fact that realism is a two-pronged term. It depends partly on the content or complexity of the given scene and partly on the perceptual characteristics of the observer in terms of his perceptual set, central nervous system mechanisms, and peripheral receptors. All of this is to say that the observer brings with him to the visual scene certain expectancies as to what the scene should be like and these expectancies dictate what is figure and what is ground. Also, these expectancies will serve somewhat to reject or accept a given scene which defines it as more or less realistic and these are as much individual idiosyncrasies and situational expectancies as they are idiosyncrasies inherent in the given scene itself. However, it is possible to dichotomize the type scene into a realistic scene and a stylized scene.

The realistic scene is that which approaches the natural scene. For example, a tree that looks like a tree. Whereas the stylized scene would be a scene in which an object is representative of a given natural object but does not necessarily look precisely like the object. For example, here a pole with a circle or sphere on top would be identified as tree. A second illustration would be that in which a stylized drawing of a triangle is identified as an airplane while the actual picture or generated display of an airplane with characteristics making it look like an airplane (i.e., wings, empennage, etc.,) would be the more realistic of the two. Obviously this requires judgment on the part of pilots or other groups of people to categorize given pictures, objects, etc. as being either more or less stylized or more or less realistic.

The question is next raised as to what texture is to represent and how texture itself is to be represented in the scene. Texture is another of these variables which would require a molar approach in the initial stages in order to make some determination as to later quantification for purposes of definition. At this point, to illustrate the general variable, one might propose that texture could be dichotomized into those texture which are stochastic and those which are deterministic. This, of course, would allow for experimentation on the basis of whether a texture was stochastic, i.e., natural or random or deterministic.

According to Pickett[6] texture may be defined in two quite different ways: as an abstract optical design and as a visible property of materials. There are advantages to each definition and the abstract definition provides a basis for the purely mathematical or statistical specification of texture

and yields a firm basis for agreement on what the stimulus is that we are talking about, according to Pickett. Considering the variable, texture, it could be said that it is perhaps one of the more important variables to be included for investigation in the category of image content. This is because texture perception provides basic, physical information with regard to the size, shape, position, and orientation of objects, surfaces and other batches of visible substance (cf Pickett[6]). Further, there are some indications that where molar patterns of color, shading, or shape are minimized or totally absent, texture may be a very critical source of information for determining the shape of a surface and the position and orientation of objects. Certainly it has proven useful in providing information about the relative distance of objects and parts of objects from the viewer. For these reasons and for others which might be derived readily, it is apparent that texture is an important variable to be researched in any study of images of visual simulation, particularly in providing rate information.

The variable that has lent itself to a more precise quantification is the variable of detail. Two approaches have been taken for the quantification of this variable in visual simulation. The approach that has been used by General Electric in their computer image generations has been that detail might be specified in terms of range. They have indicated that in switching from model levels of detail, range is the principle criterion and they have established range limits which would be used to specify the amount of detail which is required. This is based primarily on the fact that as distance from buildings or other objects is increased the small features become quite small on a display screen and when they become

comparable to the display element size they no longer provide visual cues of any significance. Thus, level of detail, as it were, fades as the subjective distance from the displayed object is increased. As an illustration, they propose that the first level of detail might be for close proximity up to about 1,000 ft distances from the object, a second level might be used from 1,000 to 3,000 ft, a third level from 3,000 to 12,000 ft. They suggest that beyond 12,000 ft the object would no longer be selected for processing.

As an alternative to the G.E. approach this study examined the concept that detail may be quantified in terms of the number of faces crossed by a horizontal line in the central viewing area of the display. Additionally, the average number of places for adjacent lines may be used as a relatively stable measure over different scenes. For a scene described by the edges bounding faces, the number of stop-after-start edges is a count of the number of faces and hence is also a measure of detail. Using the computer generated display as an example, the number of stops-after-starts per line or average number of lines will describe the amount of detail of the image. It should be emphasized that this says nothing about the so-called meaningfulness or realism of the display. Also, this should apply equally to any method or system of display presentation, be it computer image generation or film display.

Figure 2.2 is a block diagram of a generalized experimental design of the type which could be used to test the variables subsumed under the heading of Image Content. As can be seen in this design several approaches may be taken to the empirical study of the variables. For example,

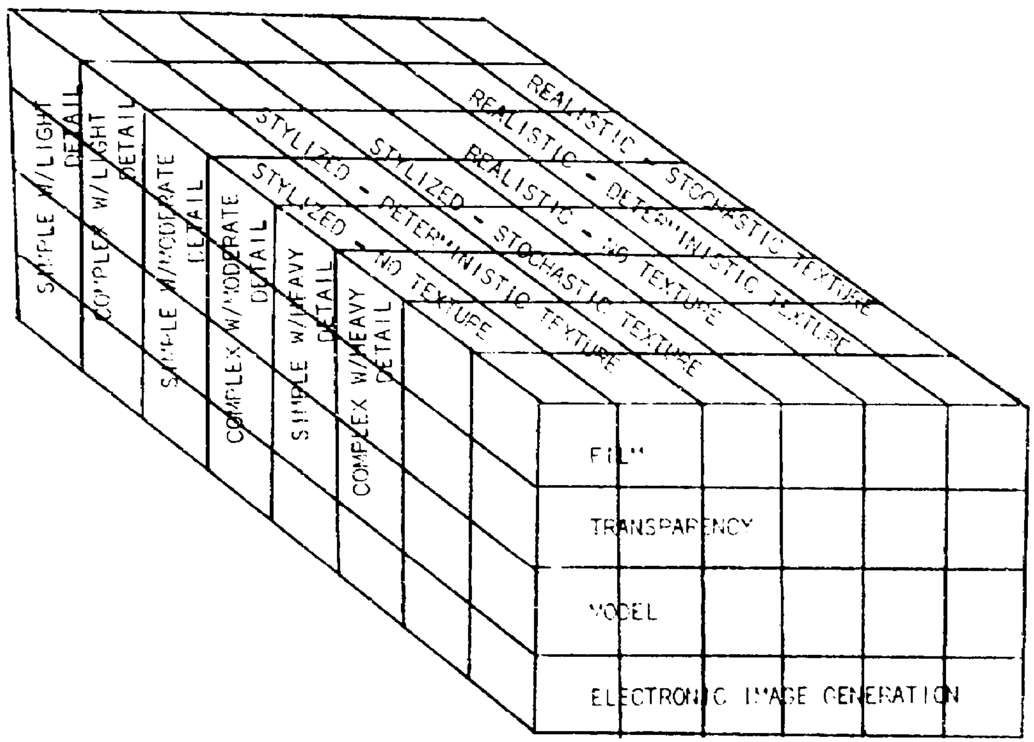

Figure 2.2 Block diagram of a Type-Experimental Design

before a final inclusion of a pattern or type of texture one might perform several experiments to determine an optimal stochastic texture and optimal deterministic texture which could then be compared with a no texture situation under two levels of realism, i.e., a realistic design versus a stylized design. The same general approach might be taken for the variable realism in that several experiments might be accomplished in the laboratory to determine the level of realism versus the level of stylization which might be used in an overall design in the same way as with texture. Obviously, it is reasonable to assume that any of these variables other than the four main effects of film, transparency, model, and electronic image generation might be used in the same way. That is, the variables could be explored independently before inclusion in this final overall design.

The design also allows for the testing of the variables listed in the four image generation approaches. Thus, if electronic image generation is available as is the case with the ASUPT program then this slice may be taken from the general design and tested. Other designs might be tested in other ways at other places or if the general simulator configuration will allow films, transparencies, and models might also be included for final testing. Thus, the design allows for the testing of method of presentation along with the content variables listed in order to test both main effects and the interactions of display type, texture, the amount of complexity, the amount of detail and whether the image should be stylized or realistic.

It should be emphasized once again that variables listed at this time in this experimental design are not proposed as the ultimate variables. At some point in a testing program it might be manifest that

these variables are meaningless insofar as experimentation is concerned and that one or more than one of these might add very little to the overall consideration of image content. However, on balance it is felt that these variables do merit at least a preliminary investigation as to their importance in the overall scheme of image presentation for visual simulations.

Another consideration which has not been presented in Figure 2.2 is that each of these blocks could be tested also in the various maneuvers which the pilot will be required to accomplish in the simulator. Taylor et al. in their study to determine requirements for undergraduate pilot training simulation systems indicated that there are various maneuvers which will be required of the pilot to include taxiing, take-off and climb, approach and landing, air work and aerobatics, formation flying, navigation and low level flying, and night flying. To adequately determine the effects and make final determinations as to workable content variables, the design needs to be tested under selected maneuvers. It is most probably true that certain of these variables have greater importance for maneuvers such as take-off and climb and approach and landing and that there would be an interaction with the manouver type and the general content of the visual image. For example, night flying would likely require little or no texture but would require the inclusion of point light souces, while take-off and climb perhaps would require a moderate to complex content and a moderate amount of detail with some sort of texture presented either realistically or stylized. Thus, maneuver becomes an important variable to be considered when applying the overall experimental design to make

some determination as to the exact content which should be included in the visual image.

2.2.5 Establishing the Trainee's Visual Environment

The trainee's visual environment as used in this context is that solid visual angle or area which he samples as he performs the various training maneuvers. It particularly includes the objects and points upon which he fixates in the performance of these maneuvers. In light of the emphasis upon the visual display content variable it was deemed highly desirable to obtain pilot's eye fixation data during training maneuvers for use in describing the visual content variable in simulation research and postulating ways of quantifying it.

The increased interest in simulating the pilot's visual environment has focused attention upon ways of determining what the display should contain. One source of data has been eye movement records of pilots performing representative flight regimes with eye movement recording devices. It appears feasible to obtain data from which to plot the solid viewing angle of the pilot and to obtain information about his sources of control information. Therefore, during the course of this project it was recommended that records of the eye movements of the Air Force undergraduate pilot instructors be obtained for use in defining the visual environment necessary for the trainee.

In collecting visual environment data it was recommended that given maneuvers be accomplished by experienced instructor pilots with immediate playback and review of the maneuver. There were two major reasons for recommending an interview and review of the record as soon as possible after the maneuvers were performed. First, the eye movement recorder recommended

for use was equipped with a 60° field of view lens. Since the observer has the capability of extending his own visual field of view beyond that point through peripheral vision, it is quite probable that information is available and utilized by the pilot which is not recorded. The interview and review of the record should cover this possibility, i.e., the extent that the pilot can recall or elaborate upon peripheral cues which were not visible in the recording.

Second, although the line of regard of the pilot can be established with the eye movement recorder recommended this would not establish the fact of the object or area on which the eye was focused. That is to say, that the eye resting upon an object would not necessarily mean that it was focused upon it. The pilot should review the recording, therefore, and identify what objects or areas he was focused upon during his points of recorded fixation.

Documentation of eye point data in the total field of view was seen not only as being of material assistance in describing and operationally defining the content variable for visual display research but could be utilized in other programs. For example, the data could be used directly by instructor pilots in directing the students attention to particular informational area in the visual field during training. Primarily, however, the records in the interviews were intended to play an important part in establishing the optimal field of view and the image content for the maneuvers recorded. These data were then to be used to structure experiments dealing with the requirements for visual simulation in ground based trainers.

The role of the eye movement recordings in an overall simulator research program is shown diagramatically in Figure 2.3. An NAC Eye Mark Recorder was obtained by Life Sciences, Inc. and transferred to the Human Resources Laboratory, Flying Training Division, AFSC, at Williams Air Force Base, Arizona. There HRL/FT personnel developed a means for obtaining and recording pilots' eye movements during flight. However, development and use of the technique did not progress beyond this stage and no data were obtained which could be used in the identification of visual display content.

2.3 MOTION-VISION INTERACTION

The problem of the interaction between information provided by the visual external world display and the motion platform is a dual one. In the first case, lack of correspondence between the two sources of information cause severe problems to the pilot in his control of the system and provide a poor learning situation. This is particularly true when the synchronization between the information from the two sources is lacking. Indications from other systems are that as little as 100 milliseconds of time lag between the motion information and that provided by the visual system presents severe difficulties for control of the system. In the second case, the required degree of fidelity of motion may not be as stringent if a good display system is present. It is a testable hypothesis that slight rates of onset of motion when combined with good visual display provides perceptually realistic information for control of the system. That is, the requirements for a high fidelity motion system is lessened with a good visual system.

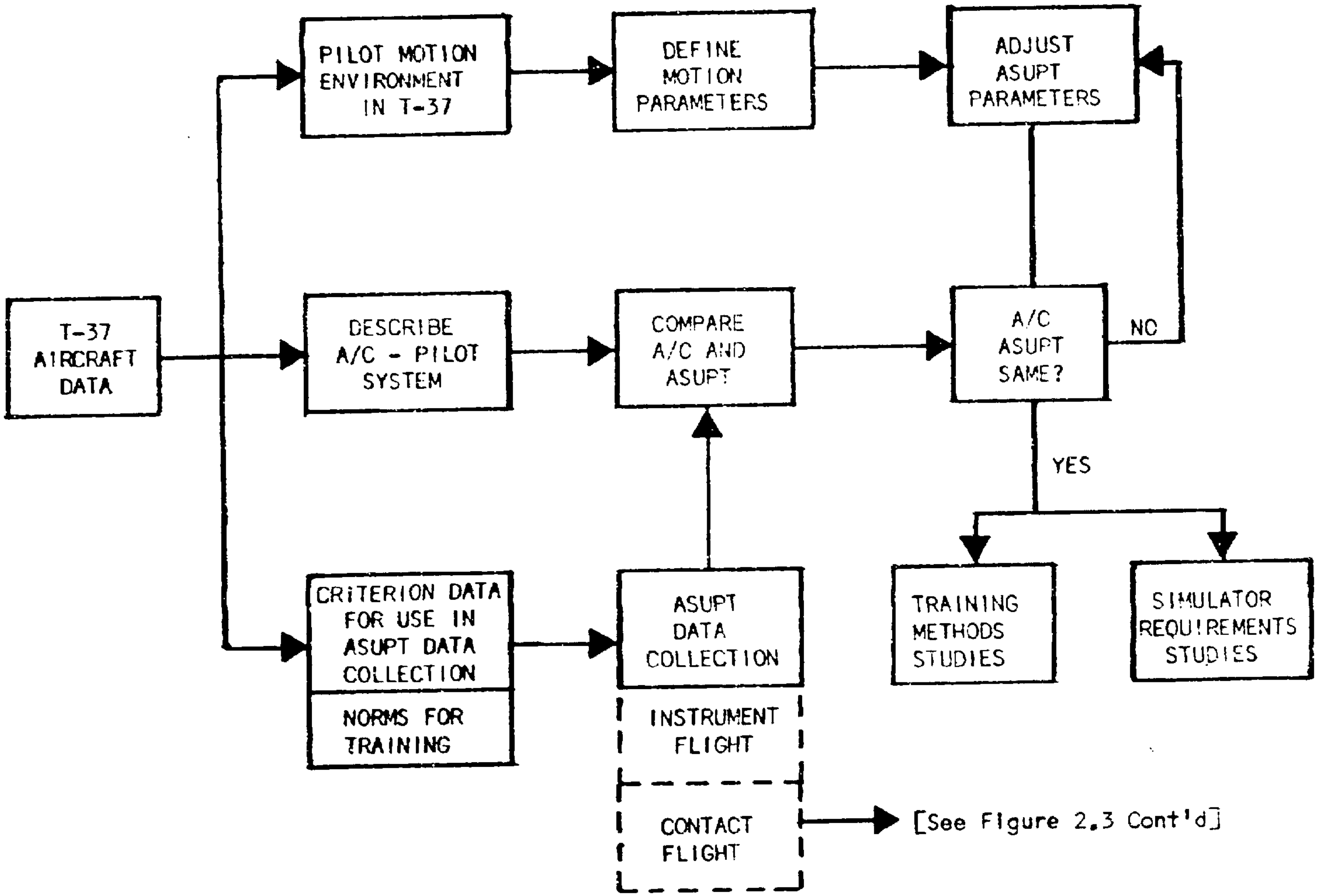

Figure 2.3 Program of events in testing performance equivalence and use of the results.

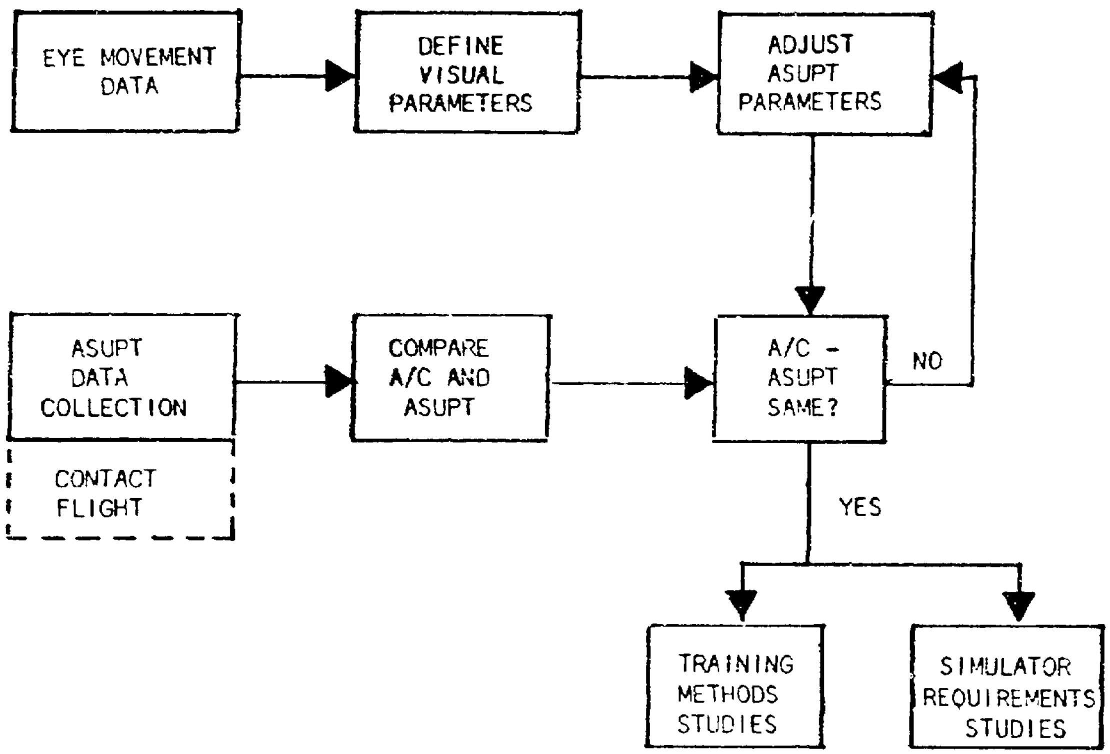

Figure 2,3 Continued

2.3.1 The Effective Time Constant Concept

The motion-vision interaction problem has been examined in the light of the effective time constant (t_e) concept developed by Matheny and Norman[7] in connection with the description of psychomotor behavior. Under this concept a testable hypothesis is that the efficiency of control behavior is a function of the time lag between the initiation of the control response and the immediacy of information feedback of the results of that response to the controller. The feedback may come through any of the human senses but in control of moving systems the primary ones are those of motion and vision. For systems with frequency responses in the range of aircraft, the motion senses perceive rates of onset of accelerations and accelerations of the system in advance of those changes in the system which are capable of being perceived by the visual sense. Thus, when the pilot is flying on instruments in which the index which he is controlling may move very little per unit displacement of the aircraft compared to the outside visual display, the motion cues are sensed well ahead of their visual counterparts. When one moves from instrument to contact flight the gain of the visual display is tremendously increased. For example, changes in aircraft pitch may be sensed in the contact scene much more quickly than through watching the artifical horizon. The increased gain in the visual display makes apparent any discrepancies between the motion and the visual information and, in particular, any lack of synchronization or phase differences between the two.

The effective time constant of a man-machine system is a function of the threshold value of the sensory mode of the operator. Rate of onset and acceleration information are perceived by the motion sensors well in

advance of the rate and position information sensed by the visual modality. However, changes in gain in visual display can lower the visual thresholds for detecting these movements which is in the case in high resolution large contact displays. However, those characteristics of the contact visual display which tend to occlude its resolution and raise the threshold of detection on the part of the operator will increase the effective time constant and can be hypothesized to increase his dependence upon motion cues.

3.0 MEASUREMENT AND METHODOLOGICAL CONSIDERATIONS

Since one of the responsibilities under the overall program was the design and detailed description of experiments relevant to the experimental questions, much consideration was given to certain methodological problems underlying this type of research. These problems fall under the general headings of (1) classical transfer of training paradigm versus performance equivalence experimentation, (2) performance measurement, and (3) economical experimental designs.

Transfer of training research has the goal of producing information which will be useful in decisions regarding the cost effectiveness of training methods, procedures and devices. What is sought is maximizing (1) the efficiency of the training system and (2) the transfer of training between that system and the criterion system. Maximum effectiveness of the training system is sought with a minimum complexity of training procedures and equipment (particularly the simulator). Once the efficiency and effectiveness of the training system has been determined its cost effectiveness can be calculated through incorporation of current cost information.

It has been traditional to evaluate a training system solely on the basis of the degree to which training in that system transfers to the criterion system. The importance of separating for study the questions of the effectiveness of the training system and the amount of transfer from that system to the criterion system has traditionally not been emphasized. The approach taken in this present work was to take advantage of the capabilities of the ASUPT to develop it into a criterion system equivalent to the T-37 training aircraft in terms of pilot performance.

Research aimed at determining the most effective methods and media for training would then use ASUPT as the criterion system. That is to say that the full capability ASUPT in which performance is equivalent to the T-37 would be used to determine those minimum characteristics of the simulator sufficient for training in particular units or phases of instruction, procedures, instructor-student interaction and automated training techniques can be studied in the ASUPT to arrive at the most efficient training system. The training systems thus derived for particular units or phases of instruction could then be used in a small number of transfer of training experiments to determine their effectiveness in training for the final criterion system - the T-37 aircraft.

The concept of efficient and effective training systems is illustrated when two different training systems result in the same transfer of training to the criterion system but accomplish the training through different methods, procedures or training equipment. One training system may be much more efficient than the other in terms of its use of trainee and instructor time, complex equipment and procedures. Conversely, two equally efficient training systems may exhibit differential transfer to the criterion system. That is to say, that a student might progress to criterion performance in one system as quickly and efficiently as in another, however; the two systems may not be equivalent in terms of the transfer of the training from them into the criterion system.

The distinction between the efficiency of the training system and the degree to which training in that system transfers to the criterion system is a concept which is fundamental to the experimental approach and

methodology being developed in this work. It is contended that the classical transfer of training experiment, aside from its other inconveniences, is not an effective method for determining the efficiency of the training system. This can best be done after establishing performance equivalence between the ASUPT and the T-37 aircraft and then using ASUPT as the criterion system. The more classical transfer of training experiments would then be limited to the final question of the degree of transfer to be obtained from maximally efficient system derived from research using the performance equivalence approach. Further, and just as importantly, the performance equivalence procedure may be used to evaluate the adequacy with which any given simulator represents the aircraft in terms of required control behavior.

3.1 CLASSICAL TRANSFER OF TRAINING PARADIGM

The classical transfer of training experiment is designed to determine the differences in training time on the criterion task as a result of training in two different situations. Typically, time to attain criterion in the criterion task after training under an experimental condition is compared to conventional training. It is important to note that in setting up the new or experimental training system numerous alternatives with respect to simulator configuration, training methods, procedures and curricula will have been considered and chosen among. The classical transfer of training paradigm offers only a very expensive means of determining which combination of these is the most efficient for attaining that level of performance which may be set as a prerequisite for transferring to the operational system.

It is important to examine the problem of deciding what the experimental configuration of the training simulator should be in the classical transfer of training paradigm. Before such an experiment can be performed it is necessary to define the range and levels of the simulator variables to be used in the experiment in a manner congruent with the perceptual capabilities of the human operator. It is necessary to determine over what range any physically defined parameter of the simulator is perceptable to the operator and, within this range what the discriminable intervals of that parameter are.

By way of example, it is possible to define a range of simulator platform motion and to designate various levels of categories within that range which may be considered as levels of the experimental variable. At the same time, however, those intervals which have been decided upon on the basis of some physically measurable parameter of motion may be indistinguisable to the human operator. Thus, each classical transfer of training experiment dealing with characteristics of the training simulator should logically be preceded by experiments establishing the perceptual range and discriminable intervals of the physical variable under study.

The suggested alternative to the classical transfer of training paradigm is that which we have termed the performance equivalence approach. This approach concept is discussed in the following section.

3.2 THE PERFORMANCE EQUIVALENCE RESEARCH APPROACH

As stated in the previous section the classical transfer of training experiment is time consuming, expensive and subject to a number of constraints. If one apparently reasonable assumption is made, the need

for the classical transfer experiment may be eliminated. This assumption is that the transfer of training between the simulator and the aircraft will be high and positive if the simulator is equivalent to the aircraft in terms of performance requirements on the operator. This means that the measured man-machine system output and the operator performance or input into the simulator controls are not different from those exhibited in the aircraft during the performance of given maneuvers under given conditions. How performance equivalence is established and what it means both in terms of determining the requirements for the training simulator and its usefulness in research dealing with training methods is the subject of this section.

The performance equivalence approach to the transfer of training problem requires that the performance of both the man-machine system and the operator be determined in the criterion vehicle. In the case of motion-vision research with the ASUPT this criterion vehicle is a T-37 training aircraft. The performance measures for the man-machine system and the operator which are required in order to establish performance equivalence are discussed in Section 3.3 below.

Once performance equivalence has been determined over the range of aircraft maneuvers of interest and under representative conditions of other variables, e.g., turbulence, the performance equivalent simulator may be used for two distinct purposes. These are (1) the determination of the minimum set of characteristics of the simulator which are equivalent in terms of performance to the aircraft and (2) its use as a criterion system in research on the most efficient methods of training,

simulator utilization, instructor-student interaction, student motivation, and a host of other important training questions.

It is not suggested that the performance equivalence approach to the transfer of training question will result in that configuration of the simulator which will maximize transfer of training since it is quite possible that simulator characteristics which are much more "difficult" to control might result in a greater amount of transfer to the criterion aircraft. At the same time, however, such a simulator might not be the configuration which is best for most efficient training in the training system.

The performance equivalence approach is recommended for establishing the basic or minimum characteristics for the training simulator and, using this equivalent system, the establishing of the most effective combinations of methods, procedures and other training media for bringing the trainee to criterion performance in the training system. This training system could then be used in a definitive transfer of training experiment to determine the savings in aircraft training time brought about through using the training system.

3.3 PERFORMANCE MEASUREMENT

One of the first questions to be answered in the comparison of two systems using performance equivalence is the manner in which the performance is measured. Traditional measures for system output exist and a good deal is known about their inter-relationships. In the aircraft system such measures as altitude, airspeed, rate of climb and bank and pitch angle are measures which reflect the performance of the man-machine combination. (These system output measures are shown as MP_2 in

Figure 3.1) As the human operator moves from one system to the other he can adapt, within limits, to the control requirements of the system in

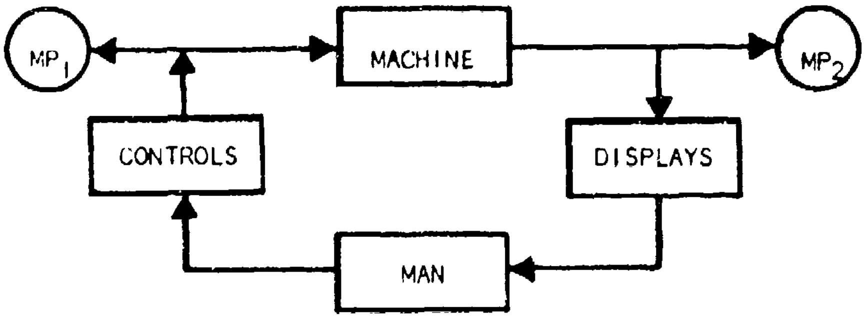

Figure 3.1 Performance Measurement Points (MP) in the Man/Machine System

order to make it perform to a certain level of system output. (The operator's control input behavior is shown as MP$_1$ in Figure 3.1.) For example, the trained pilot can adapt to the quite dissimilar control requirements of a helicopter and a fixed wing aircraft in producing the same system output for the two vehicles. That is to say that he can adapt his control behavior quite markedly in order to make the vehicles perform in identical fashion. Similarly the operator of an automobile can adapt his control input behavior to successfully cope with the differences in steering ratio and response dynamics of the large passenger vehicle and the small sports car. It should be noted here that this adaptive behavior is critical to transfer of training. The transfer of training literature and experience indicate that positive transfer of training can and does take place from a vast

variety of sources and modes of training. These range from cognitive rehearsal to practice in the actual aircraft. The central point is that the trainee can adapt his repertoire of behaviors to the requirements of the system but adaptation takes time. The more nearly his learned responses are like those required in the criterion system the less the adaptation time will be expected to be. The training literature also indicates that the trainee would experience greater difficulty in adapting to a changed response than to a changed stimulus. Thus, the importance of attention to the control input behavior being shaped by a given training device can not be overemphasized.

Measures which reflect how the operator adapts his control behavior to changes in the control element dynamics have been the subject of investigation for some time although not as intensively as have system output measures. One of the earliest serious efforts in this regard was the work of Fitts, Bennett and Bahrick[8]. Fitts et al. were interested in descriptions of the tracking control behavior of the operator in closed-loop dynamic systems. Much of the work concerned with operator input behavior has followed the example of Fitts and has looked at ways of describing the frequency and extent of the operator's control inputs. A summary of these investigations is contained in the report by Matheny[9] prepared and presented during the course of this project.

During the course of this project a great deal of effort was concentrated upon an attempt to gather data to develop operator output measures and test the feasibility of the performance equivalence concept. An unusual potential for doing this was afforded by the existence of an

instrumented T-37 training aircraft and the ASUPT simulator system for that aircraft.

As indicated in the Introduction to this report an overall program of pilot training research in motion and visual display simulators has a major aim of this project. The major features and interrelationship of the program developed during this project is shown in Figure 3.2. While this program is discussed in more detail in Section 4.0 it is presented here to indicate the pivotal role designed to be played by the data collected from the T-37 aircraft.

As shown in Figure 3.2 one of the first steps in comparing the ASUPT and T-37 aircraft systems was to collect data in both the aircraft and the ASUPT. From these data the quantitative description of the pilots control behavior in flying the aircraft was projected to be developed for use in making a performance equivalence comparison to the ASUPT.

The collecting of data in the T-37 aircraft was troubled by both administrative and instrumentation problems. Administrative problems centered primarily upon where the flights would be flown, i.e., Wright-Patterson Air Force Base or Williams Air Force Base. The obvious instrumentation problems were surmounted without great difficulty. Others could not be detected and isolated until the detailed analysis of the data was undertaken. These problems are discussed in Appendix A which deals with the analyses conducted within the limited time frame left for such analysis after T-37 aircraft data collection was accomplished.

Data from the ASUPT for use in comparing the ASUPT and T-37 system was limited to one flight due to a number of technical problems, priorities and

coordination with on-going activities at Human Resources Laboratory, Flying Training Division.

In summary of the progress in developing measures of pilot control behavior and test of the performance equivalence concept, while data was collected in the T-37 aircraft, certain instrumentation anomalies were present in the data which require more extensive data handling before analysis than was expected. The potential usefulness of the data is as great as originally anticipated for developing descriptions of pilot behavior. With respect to comparisons with ASUPT these are placed in doubt by the unexpected report by key personnel working with ASUPT that it could not be modified to accommodate the tests necessary. Although this conclusion needs further examination the necessary time was not available to make progress in this area.

The concept of performance equivalence can not be said to have been tested from the data analysis conducted to the time of writing this report. Delays in collecting the aircraft data allowed time for only the beginning analysis described in Appendix A. These analyses indicate that more complete analysis would be most fruitful for (1) identifying the descriptive coefficients for the pilots behavior useful for making comparisons between aircraft and simulator, (2) delineating the conditions under which ASUPT measures should be taken for studying comparability of the two systems, (3) providing normative data as to expected student criterion performance for both system output and operator input measures and (4) provide operator input measurement techniques for use in developing teaching techniques, either conventional or adaptive, which concentrates upon shaping the trainees control input behavior.

4.0 MOTION-VISION RESEARCH PROGRAM

The investigation of vision, motion and their interactive effects was considered as an overall program of research in which the ASUPT system would play the major role. In brief, the ASUPT system was proposed to be made equivalent to the T-37 aircraft in terms of pilot behavior required to perform certain maneuvers to specified criteria. The maximum capability of the ASUPT would be utilized in adjusting its parameters to configure it so that the pilot control requirements were the same as those acquired in the aircraft. The overall program is shown diagramatically in Figure 2.3, Page 31.

The sequence of studies was designed to investigate first the motion characteristics of the simulator with only internal instruments as visual displays. This was done because it was felt that the application of the performance equivalence concept should be first applied to the situation in which the experimental variables, i.e., motion of the simulator, could be specifically defined with the visual display of information identical to that of the aircraft. This approach was also coincident with the schedule of delivery of ASUPT equipment and its availability for research.

As pointed out in Section 2.0 the characteristics of the motion imparted to the system by the external forcing function of turbulence is of extreme importance in the study of motion cues. As shown in Figure 2.3 the T-37 aircraft data was designed to be used in the determination of these forcing functions as indicated in the block entitled "Pilot Motion Environment in the T-37." These data were then to be used in the definition of motion parameters and their implementation in the ASUPT system as discussed earlier. The block entitled "Describe

Aircraft-Pilot System in Figure 2.3 and that entitled "Compare Aircraft and ASUPT" indicates the steps and investigations discussed under Methodology and Measurement Considerations in Section 3.0. Based upon these data the adjustment of ASUPT to be equivalent to the T-37 aircraft was projected to be accomplished followed by simulator motion requirement studies. The general design of these studies was aimed at determining the minimum number of dimensions and the minimum degree of fidelity of physical simulation defined in terms of bandwidth of response of the motion platform at which performance was still equivalent to the full simulation.

In Figure 2.3 is shown also the use of eye movement recordings in the approach to the definition of the visual parameters to be studied as visual display characteristic of the simulator. The eye movement data was programed to play a prominent role in identification of the positions of objects in the external scene and the internal referents used by the pilot in control of his aircraft. The procedure to be followed was identical to that in the study of motion requirements in that the simulator would be configured to be equivalent to the T-37 aircraft in terms of pilot performance using the maximum capability of the ASUPT device. Assuming this could be accomplished, the subsequent experiments would be aimed at determining the minimum necessary and sufficient characteristics of the visual display for bringing about performance of the pilot equivalent to that in the T-37 aircraft.

The extent to which the research program was accomplished has been outlined in the previous Sections. In brief, although T-37 aircraft data was collected the delay in its collection allowed time only for the briefest preliminary analysis of the data. With respect to definition

of the visual parameters, an eye movement recorder was obtained and configured for use in the then T-37 aircraft. Data collection feasibility was then tested. However, only tentative data for specifying positions and characteristics of internal and external references were obtained.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The overall object of the project of investigating the role in the training simulator of motion, visual display and their interaction was not accomplished. The important first steps necessary to their investigation, i.e., explicit description and quantification as experimental variables, was made and is presented.

Due to the extremely large number of states of the experimental variables in dealing just with motion and visual display attention was given in the greater portion of the work to development and test of more economical methods of experimentation. The concept of the performance equivalence between the simulator and the aircraft was presented along with the arguments for the importance of pilot input measures in addition to system output measures in research on training devices. An attempt was made to take advantage of the opportunity for obtaining pilot performance data both in an instrumented T-37 training aircraft and the research simulator of that aircraft, the ASUPT. Delays and difficulties in collecting data both in the aircraft and in ASUPT allowed time for only preliminary but promising analysis of the aircraft data. Certain data recording anomalies in the form of spurious signals make it necessary to carry out more data clean up than was anticipated. Nevertheless, the opportunity for developing and testing a new approach to establishing quantitative indices of the degree of correspondence between aircraft and simulator based upon operator control behavior is present with these data. It is recommended that the opportunity not be lost and that the analyses be carried on.

In the conduct of this project an overall program for systematically investigating the motion and visual display variables was outlined. The carrying out of the plan if successful would provide quicker and more economical answers to both simulator characteristics and training methodology questions provided the necessary funds and personnel support could be brought to bear on the problem. It is recommended that the program be pursued.

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APPENDIX A

I. Summary Progress in T-37 Aircraft Pilot Control Behavior Analysis

1.0 Purpose of this appendix is to present:

1.1 The detailed method of analysis used to develop a linear, time variable pilot identification for the T-37 aircraft in-flight data.

1.2 A critique of the method used and of the data available for analysis.

1.3 Suggestions for improving the methodology and data preparation.

2.0 Summary

2.1 The full sequence of the operations needed to accomplish the pilot discrete time state equation identification as outlined in the addendum to this appendix has been implemented. Five pilot states were assumed.

2.2 A single spurious data pulse in all channels resulted in a discernable difference in trend of the identified coefficients.

2.3 The identified coefficients show cyclic trends, as they did in preliminary identification analyses.

3.0 Conclusions

3.1 Use of the actual input numerical data in the identification yields misleading results. Error values of the inputs from a standard are necessary.

3.2 Spurious instrumentation signals attenuated the results of the Fourier analysis to some extent and indicated the necessity for a data smoothing process.

4.0 Recommendations for further and complete analysis of the data.

4.1 Use input error values in the identification rather than absolute values.

4.2 Remove the spurious signals from the data.

4.3 Transform heading into a continuous sequence.

4.4 Seek a better criterion for Fourier Series truncation to select fewer terms for coefficient identification analysis.

4.5 If implementation of items (1) through (4) still yields rapidly varying coefficients, increase pilot state dimensions, (e.g., elevator deflection rate) and add possible cue signals (e.g., rate of climb and/or rate of onset of acceleration (jerk) until slowly varying identified coefficients result.

5.0 Data preparation and identification method.

5.1 The methods used were those outlined in Addendum I., except as noted below.

5.2 It was evident from review of the summary listings of the missions flown in the T37-1948 aircraft provided by Wright-Patterson AFB that there existed many spurious points in the data. The summary listings provided a print out every 2 seconds or at every 40th data point. These spurious values were due to an unidentified source which produced saturated or near-saturated signals at random - appearing intervals. In order to avoid data contamination a mission was selected which appeared from scrutiny of the summary listings to contain no spurious points.

5.3 One maneuver, a 30° left bank at 100 knots airspeed flown under contact conditions, was selected for prototype analysis. The summary listing for the maneuver appeared to contain no anomalies for any of the recorded variables.

5.4 Twenty-two (22) recorded variables were selected for analysis. Five (5) of these were hypothesized to be measurements of pilot state variables (Ψ). These were elevator, aileron, rudder, aileron trim tab and throttle positions. The remaining seventeen (17) variables were hypothesized to be measurements of the pilot input variables (μ): These were elevator stick force, aileron, stick force, rudder force, airspeed, altitude, heading, pitch angle, pitch rate, roll rate, yaw rate, pitching acceleration, rolling acceleration, yawing acceleration, and longitudinal, lateral, and normal acceleration at the pilot's station. These variables were to be used to identify the pilot by the discrete time form:

$$\underline{\Psi}_{i+1} = A_i \underline{\Psi}_i + B_i \underline{\mu}_i \quad ,$$

where A_i and B_i are slowly time varying functions relative to the length of the maneuver.

5.5 The measurements were presumed to be contaminated with noise due to inaccurarcies of recording instruments, resolution of the recording instruments, inaccuracies and resolution of pilot control movements, atmospheric turbulence and other unidentified sources. In order to reduce the effect of random disturbances upon the pilot identification procedure, the raw data was processed to remove some identifiable randomness and as a consequence maximize the deterministic content of the data. The processing

method was not intended to remove the effects of the spurious signals mentioned in 5.2, which appeared to a randomly occuring signal of fixed magnitude.

5.6 The power spectral density of the first 2048 points (out of a total of 2400 points) of the two minute maneuver was computed for each of the 22 variables. A fast Fourier transform routine was used to compute the power spectrum. A print out and a plot of the power spectra of each of the 22 variables are available for inspection as data listing in "Matheny FFT 1-22." The spectra were hypothesized to be composed of the composite spectra due to deterministic signal and of random noise. An earlier preliminary power spectral analysis of two variables (elevator and altitude) in a stall maneuver from another mission it was determined that beyond a certain frequency all the spectral values were of essentially constant magnitude (i.e., the spectrum was flat). For those frequencies for which the spectrum was flat, it was assumed that the major contribution to the time history of the signal was due to a random sequence. Since beyond a certain frequency there is essentially no determinism in the signal, i.e., it is a random sequence, the signal was programed to be smoothed to contain no frequencies greater than that at which there was only noise. This program is accomplished by truncating the Fourier series describing the variable. This does not preclude the existence of randomness in the remaining terms of the series.

5.7 From the examination of the power spectra of the elevator and altitude variables described in (Section 5.6), it appeared that

the power spectra consisted of a few low frequencies of large magnitude decreasing monotonically to a flat spectrum of smaller magnitudes. The average value of the power spectrum over all frequencies appeared to be slightly greater than the mean value of the flat portion of the spectrum. Consequently a criterion was established for truncation of the spectrum. This involved selection of the highest frequency which had a spectral value greater than the mean spectral value and elimination of all frequency components greater than that frequency.

When the power at zero frequency was included in the computation of the mean the mean spectral power was so large for some variables (e.g., altitude) that only the value at zero frequency had a power greater than the mean. Consequently the power at zero frequency was eliminated from the computation of the mean spectral power. This resulted in considerably more spectral components being retained in the smoothed variable.

Due to an error in the algorithm the variables in prototype analysis were smoothed by counting the total number (N) of frequencies with spectral value greater than the mean spectral value and using the first N frequency components to regenerate the time series. Using this criterion the smoothed data was generated utilizing from 30 to over 480 terms of the Fourier series. For any number of terms selected, the resulting curve represents the least squares fit to the original data. The least squares fit is printed and plotted in "Matheny FFT 1-22"

for each of the 22 variables along with the raw data on the same coordinate axes. The Fourier coefficients used to regenerate the smoothed data are listed in "Matheny FFT 1-22" and appear in summary in "Matheny Merge."

5.8 The identification was performed on the smoothed time histories described in 5.7. The pilot was identified as a linear fixed order system with 17 inputs with time variable coefficients. There were seventeen identification intervals over the maneuver. The A_I and B_I matrices are listed in "Matheny ID 948." The number of identification intervals is determined by the averaging criterion indicated in the addendum.

5.8.1 In the seventh identification interval the singularity of a matrix which requires inversion in the identification algorithm precluded the completion of identification for that interval.

5.8.2 A cursory examination of the coefficients of the A and B matrices revealed that the coefficients for the thirteenth identification interval were generally atypical from the coefficient trend from the beginning of the maneuver to the end. On the average they were of unusually large magnitude in comparison to neighboring values. The single spurious value at 82 seconds enters into the computation of the a and b coefficients in the thirteenth interval. The effect of the data smoothing procedure is to increase the effect of the spurious coefficient on the identification process since the smoothing procedure

affects values of the variables approximately one second on either side of the spurious point. The signs of spurious points do not appear to have any correlation with the normal sign relationship of the data.

5.9 In order to present the A and B matrix coefficients in a summarized form, a Fourier series was fit through each of the coefficients. A fast Fourier transform routine was used on the first sixteen coefficient intervals. Since the seventh interval coefficients were undetermined, the seventh interval coefficients were replaced by the mean values of the sixth and eighth interval coefficients. In order to compare the effect of the thirteenth interval coefficients, two runs were made one with the thirteenth interval coefficients as computed and one with the thirteenth interval coefficients replaced by the average value of the coefficients of the twelfth and fourteenth coefficients. The coefficients of the Fourier series for these two cases did not appear to be significantly dissimilar. No statistical tests were made, because of time constraints on the project. Fourier coefficients for the A_i and B_i matrices are listed in "Matheny FFT * AB (thirteenth coefficient as computed) and "Matheny FFT * AB2. (Thirteenth coefficient computed by averaging the 12th and 14th coefficients).

6.0 Critique of the methodology and suggestions for improvement.

6.1 The presence of spurious points is definitely detrimental to the method of analysis. Even in a maneuver with no spurious values apparent from examination of the summary

listing, spurious values appeared in all 22 variables. In 20 of the variables these values appeared at 82 seconds. The magnitude of these values were from 2 to 200 times the magnitude of the normal range of values of the variables during the maneuver. Usually the values at the spurious points were ten times normal magnitudes. Two of the variables, elevator position and rolling acceleration had six and seven spurious points, respectively. Due to the influence of these spurious values on the identification routine, it is necessary to remove these points from the raw data before proceeding with the analysis. It will be necessary to examine a listing of each variable or to devise a computer routine which identifies values which change rapidly in .05 seconds.

6.2 The smoothing of the raw data is necessary to the identification procedure because of the accuracy and resolution of the recording instruments relative to the range of the variables recorded. The ranges of 15 variables are less than ten times the accuracy of the instruments used to measure these variables. For 5 of these 15 variables the total range of the variables is less than or equal to the accuracy of the respective recording instrument. For the elevator the total range is only ten times the resolution of the recording potentiometer. Consequently, filtering the raw data to remove the uncertainty due to instruments is necessary.

6.3 The raw data for heading contains discontinuities as the heading goes through 0° (360°). It is necessary that the

data be transformed to provide a continuous variable from 0° to multiples of 360° before processing.

6.4 The method used to truncate the Fourier series should be revised. Visual inspection of the power spectrum of each variable and estimation therefrom of the number of frequencies which should be used in the truncated series approximation of the variable indicated that significantly fewer frequency components should be used. In some cases the routine used two orders of magnitude more frequency components than estimated thus unnecessarily extending the computational requirements.

6.5 The pilot input variable ($\underline{u}_i$) should be rewritten so that the identification procedure utilizes the true variables upon which the pilot acts. For example, in the 30° bank, the pilot manipulates controls in response to the difference between the actual bank angle of the aircraft and the desired bank angle (30°). Similarly, the signal to the pilot for a constant airspeed criterion is the difference between actual airspeed and desired airspeed. Some of the pilot state variables which are deviations about a non-zero position (e.g., elevator position) should be rewritten for the identification procedure about a zero reference position for the maneuver. Some of the apparent sign change and time variable behavior in the A_i and B_i matrix coefficients may be due to the analysis of actual values rather than error values.

6.6 The pilot may not be adequately described by a fifth order system. The number of states describing the pilot may be increased by augmenting the state vector used in this analysis with the derivatives of these states. In order to estimate these derivatives the smoothing of the variables provided by the power spectral density method described in 5.6 and 5.7 is essential.

6.7 As an additional comment on prospective Maximum Likelihood Parameter Estimation, in view of the fact that neither the exact functional form nor the number of states of the pilot are known, none of the statistical conclusions which are implicit and explicit in its structure can be made.

ADDENDUM TO APPENDIX A

1.0 Purpose.

The purpose of this addendum is to detail the rationale for analysis of the T-37 instrumented aircraft data.

2.0 Summary.

2.1 Because of the nature of the problem, the strategy adopted was:

2.1.1 analyze the power spectral density of each measurement by utilization of the Fast Fourier Transform.

2.1.2 account for the content of randomness in the measured data.

2.1.3 accomplish the identification process.

2.1.4 express the identified coefficients as finite Fourier series.

3.0 Background.

On first considering the problem it was proposed that the standard state-space based methods of modern control theory would be appropriate to determine the equations which would predict the behavior (as reflected by his manipulation of the controls) of a human pilot during a specified maneuver.

It was expected to be necessary to use either the form (continuous time)

$$\underline{X}\,(t) = A\,(t)\ \ \underline{X}\,(t) + B\,(t)\ \underline{U}\,(t)$$

or the form (discrete time)

$$\underline{X}_{i+1} = \underline{A}_i \quad _i + B_i\ \underline{U}_i$$

It was thought possible that the X_i's would be the aircraft controls' positions and the U_i's would be the measured cues which help a pilot make

his decisions. It was recognized, however, that the pilot might have more significant states than the number of aircraft controls and that there might be other significant inputs (besides measured cues). In particular, spurious pilot and measuring system behavior was an item of concern as was rate of climb and pilot "dither".

It was decided to proceed in such a way as to minimize cost of the project which involved formulating the following hypotheses:

(a) the discrete time form with an uncertainty vector is adequate

$$\underline{X}_{i+1} = A_i \underline{X}_i + B_i \underline{u}_i + \underline{n}_i$$

(b) the aircraft controls' positions are the states, and measured cues are the inputs.

(c) the coefficients, A_i and B_i are slowly time varying

$$(|A_{i+100}/ A_i| \lesssim .1 \quad \& \quad |B_{i+100}/ B_i| \lesssim .1).$$

(d) the uncertainty, $\underline{n}_i$, is a random sequence with zero mean.

(e) the measurement of the state, $\underline{YX}_i$, differs from $\underline{X}_i$ by random variable sequence with zero mean $\underline{\omega X}_i$, and the measurement, $\underline{Y\mu}_i$, has a similar property.

The above hypotheses give:

$$\underline{X}_i + \underline{YX}_i - \underline{\omega X}_i$$

$$\underline{\mu}_i \quad Y\underline{\mu}_i \quad \underline{\omega\mu}_i$$

and

$$\underline{YX}_{i+1} - \underline{\omega X}_{i+1} = A_i \left[\underline{YX}_i - \underline{\omega X}_i\right]$$

$$+ B_i \left[\underline{Y\mu} - \underline{\omega\mu}_i\right] + \underline{n}_i$$

Averaging over ℓ adjacent periods would yield

$$\left.\overline{YX}_{i+1}\right|_{\ell} - \left.\overline{\omega X}_{i+1}\right|_{\ell} = \left.\bar{A}_i\right|_{\ell}\left[\left.\overline{YX}_i\right|_{\ell} - \left.\overline{\omega X}_i\right|_{\ell}\right]$$

$$+ \left.\bar{B}_i\right|_{\ell}\left[\left.\overline{Y\mu}_i\right|_{\ell} - \left.\overline{\omega\mu}_i\right|_{\ell}\right] + \left.\bar{\eta}_i\right|_{\ell}$$

Given the hypotheses, if ℓ were large enough, the noise terms would be averaged to zero:

$$\left.\overline{YX}_{i+1}\right|_{\ell} \cong \left.\bar{A}_i\right|_{\ell}\left.\overline{YX}_i\right|_{\ell} + \left.\bar{B}_i\right|_{\ell}\left.\overline{Y\mu}_i\right|_{\ell}$$

and this forms the basis for our identification trateqv.

The results of preliminary analysis indicate that A_i and B_i are not slowly varying. The reason could be that there are more pilot states than aircraft controls, or the effect of large scale randomness cannot be smoothed by averaging over a few adjacent points. A third possibility is that other pilot cues than the measured ones are significant. Rate of climb is an example.

All these possibilities required consideration of more expensive approaches to the problem. Some possibilities were:

(a) An iterative maximum likelihood identification. This approach was deduced to be far too expensive.

(b) Remove the randomness (as far as is statistically defendable) from the measurements and then proceed with the identification. This procedure was much less costly and was projected to give good results.

4.0 Analysis Procedure Adopted

4.1 Make the following hypotheses.

(a) the random component is a stationary process. The probability density function has an unspecified distribution (i.e., it may be uniform, Gaussion, etc.). The conditional probabilities hence the n dimensional probability density is such that power distribution over frequency is flat up to a finite frequency, f_l, such that $f_s \leq f_l \leq f_T$, where

$f_T = \frac{1}{2T}$, T = maneuver duration

f_s = maximum frequency content of the hypothesized deterministic signal

4.2 Using the Fast Fourier Transform, obtain the finite Fourier Series which fits the 2048 data points for each measurement.

4.3 Determine the power spectral density (PSD) of each measurement.

4.4 Deduce randomness components from the high frequency components' flatness.

4.5 Subtract the (PSD) of the randomness component from the overall PSD thus yielding a PSD of the deterministic component. This is done for each measurement. (Preliminary studies show that the deterministic component is contained in the first (lowest) 3% of the Fourier spectrum). This also establishes the highest frequency of the Fourier Series of the deterministic component.

4.6 Use the Fourier Series so derived to generate data for the identification.

4.7 In the interest of economy, use the same I.D. program we have used: generate coefficients for each six (6) seconds.

4.8 Fit a 20 - term Fourier Series to the generated coefficients.

5.0 Discussion

By taking this approach, states could be added by including their derivatives, and derivatives of input can also be considered.

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